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Shear Performance of Steel Fibre-Reinforced Concrete

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ABSTRACT
This paper presents results from an experimental study and an analytical assessment on the shear performance of steel fibre-reinforced concrete. Federation Internationale de la Precontrainte (FIP) standard shear tests were conducted on normal- and high-strength steel fibre-reinforced concrete (SFRC) specimens. Test parameters investigated include compressive strength of the concrete and fibre volume fraction. It was found that the steel fibres enhance the shear capacity of the concrete up to 70 precent compared to plain concrete shear capacity. An equation, based on regression analysis, is proposed to predict the shear capacity of the SFRC.

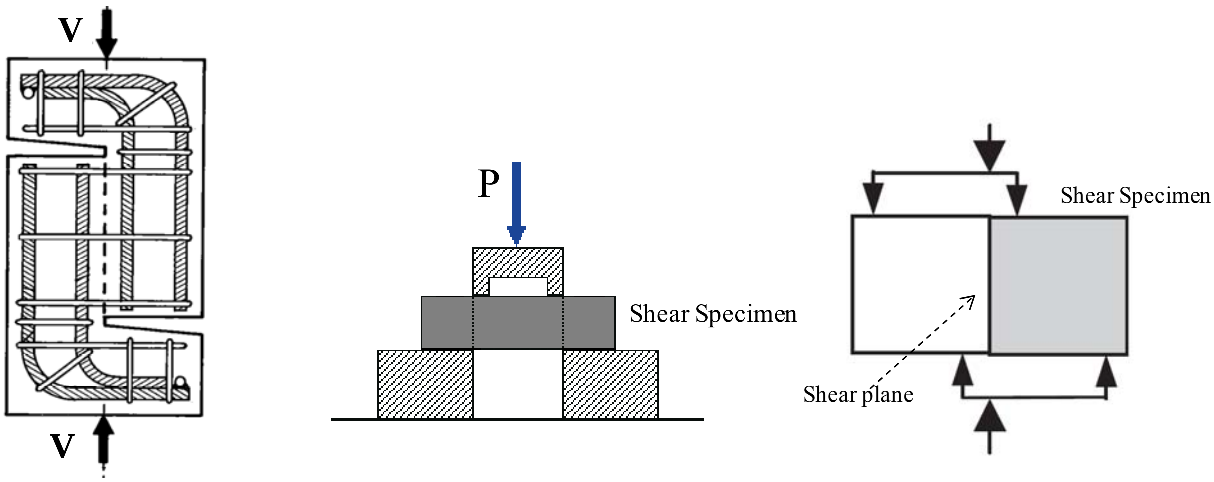
KEYWORDS
Fibre reinforced concrete; Plain concrete; Steel fibre; Shear strength.

INTRODUCTION

The brittle and catastrophic shear failure of concrete can be overcome by the addition of the steel fibres. Past studies have shown that fibres improve the shear performance of both normal-weight concrete and light-weight concrete (Higashiyama and Banthia 2008; Majdzadeh et al. 2006; Mirsayah and Banthia 2002; Valle and Buyukozturk 1993; Narayanan and Darwish 1987).

Among existing test methods for evaluating shear strength and shear toughness, Z-type push-off specimen (Figure 1(a)) has been widely used for both traditionally reinforced concrete and SFRC. This is also known as Hoffbeck-style or double L-shaped specimen. It is not a standardized test procedure, and different specimen sizes have been used in the past studies. For instance, Hoffbeck et al. (1969) used specimens 546 mm high with a cross section of 254 mm by 127 mm, Walraven and Reinhardt (1981) used 600 mm high specimens with a cross section of 300 mm by 120 mm, Van de Look (1987) tested specimens with 600 mm height and a cross section of 400 mm by 120 mm, Khaloo and Kim (1997) used 520 mm x 300 mm x 125 mm samples. Mirsayah and Banthia (2002) argued that in Hoffbeck-style push-off specimen, beyond cracking the stress conditions deviate significantly from being in pure shear and the test does not simulate pure shear. Hence, Mirsayah and Banthia used the Japanese Society of Civil Engineering (JSCE) standard method (JSCE-G 553, 1999), which is a modified version of (JSCE-SF6, 1990), for their tests (Figure 1(b)). Also, Barragan et al. (2006) mentioned that utilized technics to cast notches or using side grooves, in Hoffbeck-style push-off specimen, to avoid cracking outside the shear plane, and having reinforcing bars within the specimen could interface with fibre distribution. Moreover, preparation of Hoffbeck-style push-off specimen is a cumbersome procedure if a large number of tests have to be carried out.

Since one of the aims of the current research is to investigate the effect of precracking on the shear performance of the SFRC, using the JSCE standard (JSCE-G 553, 1999), which has two shear planes in its specimen, would not be practical. Because of the deficiencies and complexities of the aforementioned shear test methods, it was decided to conduct the shear tests as per FIP (Federation Internationale de la Precontrainte) standard (Figure 1(c)). The size of the specimen in this method is 250 mm x 250 mm x 540 mm. In the FIP's test method, the interface is theoretically subjected to pure shear forces, and the occurrence of a bending moment owing to force eccentricities is minimized (Beushausen and Alexander 2007). Moreover, these test samples are easy to construct.



(a) (b) (c)

Figure 1. Schematic of shear tests: (a) Hoffbeck-style push-off specimen; (b) JSCE-G 553 shear test; and (c) FIP shear test.

EXPERIMENTAL PROGRAM

The purpose of the program was to study the shear performance of SFRC and to quantify the material properties of SFRC in shear. The considered variables were, concrete compressive strength and steel fibre volume fraction.

Materials and concrete mix

To evaluate the effect of the concrete compressive strength, two reference concrete mix designs were developed to achieve 35 MPa and 60 MPa after 28 days. The considered fibre dosages were 20, 40, 60, and 80 kg/m^3. One type of steel fibre, Dramix RC-80/60-BN, was used in the tests. The fibres are high strength, hooked-end cold drawn produced by Bekaert. The dimensions and material properties of the steel fibres are given in Table 1. Locally available coarse aggregate (semi-crushed having maximum size of 13mm) and fine aggregate (natural river sand) were used in all concrete mixes.

Table 1. Properties of steel fibre.

Length l_f **[mm]**	Diameter d_f **[mm]**	Aspect ratio l_f / d_f	Yield strength σ_{fy} **[MPa]**	Shape
60	0.75	80	1050	

Since the inclusion of fibres significantly affect the workability properties of fresh concrete, rheological testing has been carried out to achieve an optimum mix design for each dosage of fibre. Rheological tests were conducted using the BML viscometer machine. As a result, eight mix designs were developed. The compositions of the mixes are summarized in Table 2. The mixture ID identifies the target compressive strength of the concrete and fibre dosage. For example, C3540 represents a concrete mix with 35 MPa target strength (C35), and 40 kg/m^3 steel fibre. From each mixture, three shear specimens and six 100 mm-diameter x 200 mm-long cylinders for compressive strength test (ASTM-C39, 1998) were cast. Three cylinders were tested at the age of 28 days, and the next three cylinders were tested at day of testing shear specimens. Moreover, shear samples from C3520, C3540, C3580, C6020, C6040, and C6080 mixes with no fibres added to the mix were taken to investigate the shear performance of the plain concrete mixes. These mixes are designated by C3520W, C3540W, C3580W, C6020W, C6040W, and C6080W.

Table 2. Mixture composition and properties of the concrete.

Mixture ID	Fibre Dosage [kg/m^3]	Fibre volume fraction [%]	w/c ratio	Water [kg/m^3]	Cement [kg/m^3]	Coarse aggregate [kg/m^3]	Sand [kg/m^3]
C3520	20	0.25	0.6	172	287	1040	906
C3540	40	0.51	0.6	175	292	920	1007
C3560	60	0.76	0.6	185	308	750	1129
C3580	80	1.0	0.6	190	317	600	1252
C6020	20	0.25	0.4	172	410	1040	802
C6040	40	0.51	0.4	175	417	920	901
C6060	60	0.76	0.4	180	429	750	1041
C6080	80	1.0	0.4	185	440	600	1161

Shear tests

Shear tests were conducted as per the FIP standard shear test. The schematic of the test setup and the instrumentations is shown in Figure 2. Displacements in the direction of, and normal to, the shear plane were measured using linear variable differential transducers (LVDTs). The horizontal displacement (i.e. crack width) and the vertical displacement (i.e. crack slip) were computed as the average readings generated between four and two LVDTs, respectively. In order to avoid cracking outside the intended failure shear plane a 15 mm deep notch was sawed all around the specimen. The tests were performed in a DARTEC universal testing machine with a capacity of 10000 kN. Initially loads were applied from 0 to 100 kN at a loading rate of 0.5 kN/s, subsequently the specimens were subjected to a continuously increasing shear displacement with a rate of 0.001 mm/s. Applied load and displacements were recorded at a frequency of 10 Hz. Shows a picture of the share test setup and shows a fractured SFRC specimen.

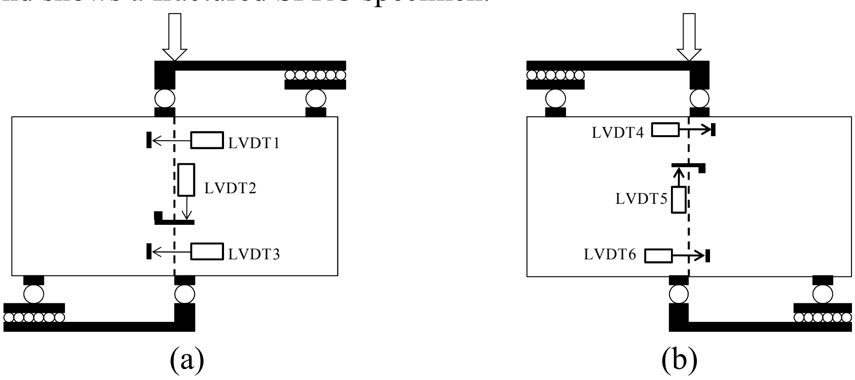


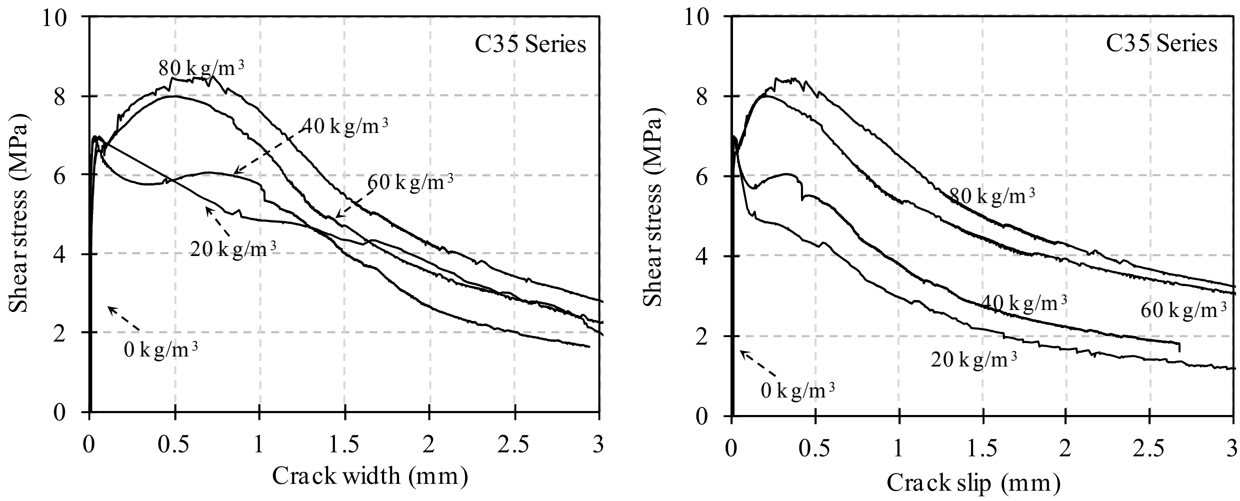
Figure 2. Schematic of shear test setup and instrumentation: (a) west view; and (b) east view

(a) (b)

Figure 3. Photograph of: (a) shear test setup; and (b) SFRC specimen after direct shear test

RESULTS AND DISCUSSION

The typical stress-crack width displacement and stress-crack slip displacement for C35 and C60 SFRC shear specimens are shown in Figure 4 and Figure 5, respectively. Each curve is an average of three curves obtained from shear tests on three shear specimens. Plain concrete specimens showed, as expected, a sudden and brittle failure at a very low shear strain. The shear stress-displacement response is linear up to the peak stress (i.e. cracking shear stress) and instantaneously the capacity to carry load beyond that point is lost. On the other hand, failure in SFRC specimens is ductile. In C35 SFRC shear specimens with 20 and 40 kg/m^3 of steel fibres, and in C60 SFRC shear specimens with 20 kg/m^3 of steel fibres the linear response up to the cracking shear stress was followed by a gradually decreasing post-peak response. The cracking shear stress was the peak shear stress in these specimens (Figure 6). In C60 SFRC specimens with 40, 60, and 80 kg/m^3 of steel fibres, and in C35 SFRC specimens with 60 and 80 kg/m^3 of steel fibres, however, there is an increase in post-peak load carrying capacity. In these specimens, as shown in Figure 6, the ultimate shear stress is higher than the cracking shear stress.



(a) (b)

Figure 4. C35 SFRC shear test curves: (a) Shear stress-crack width displacement; and (b) Shear stress-crack slip displacement.

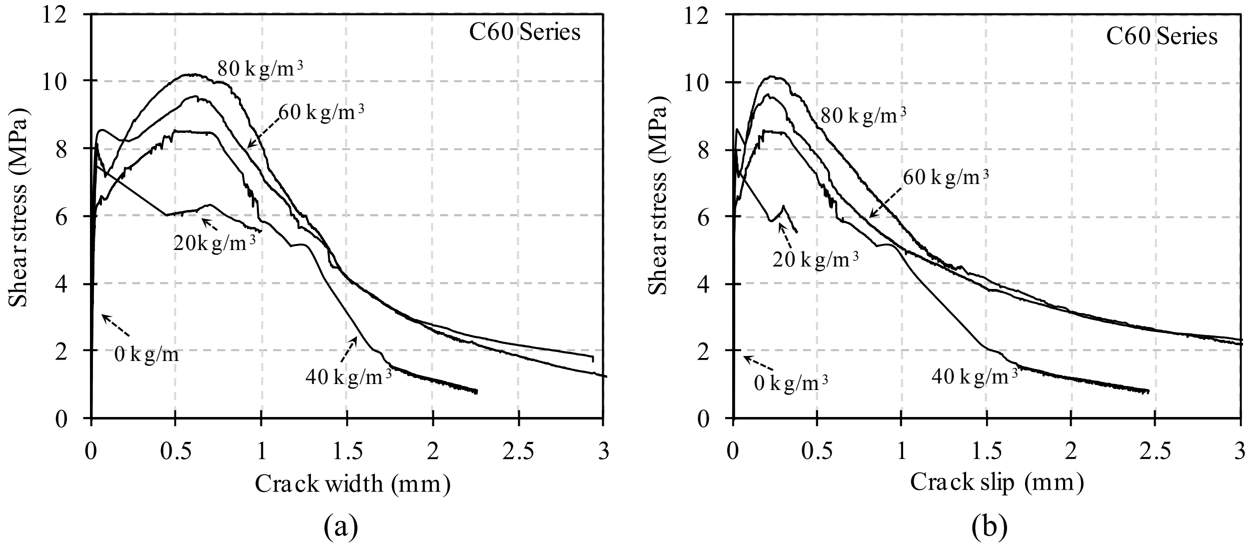


Figure 5. C60 SFRC shear test curves: (a) Shear stress-crack width displacement; and (b) Shear stress-crack slip displacement.

Ultimate shear stress and cracking shear stress of the plain concrete and SFRC specimens, along with the compressive strength at 28days and on the shear test day are presented in Table 3. A plot of the test results are also shown in Figure 6. It can be seen that addition of steel fibres has also enhanced the cracking shear stress of the SFRC samples, compared to the plain concrete samples.

Table 3. Compressive strength and shear test results

Mixture ID	$f_c'{}_{.28day}$ [MPa]	$f_c'{}_{.test\ day}$ [MPa]	τ_{crack} [MPa]	τ_u [MPa]	Increase in τ_u [%]
C3520	40.4	48.2	6.59	6.59	1
C3520W	40.2	47.2	5.10	5.10	1
C3540	40.0	46.9	6.95	6.95	1
C3540W	42.1	48.6	5.28	5.28	1
C3560	40.7	46.6	6.47	8.01	1.23
C3580	38.7	46.6	6.52	8.64	1.32
C3580W	36.8	45.8	4.70	4.70	1
C6020	65.4	72.6	7.52	7.52	1
C6020W	62.5	69.3	5.70	5.70	1
C6040	63.0	69.6	7.65	8.54	1.11
C6040W	64.4	71.3	6.20	6.20	1
C6060	60.1	67.5	8.30	9.40	1.13
C6080	65.3	72.5	7.90	10.2	1.30
C6080W	60.4	68.1	6.40	6.40	1

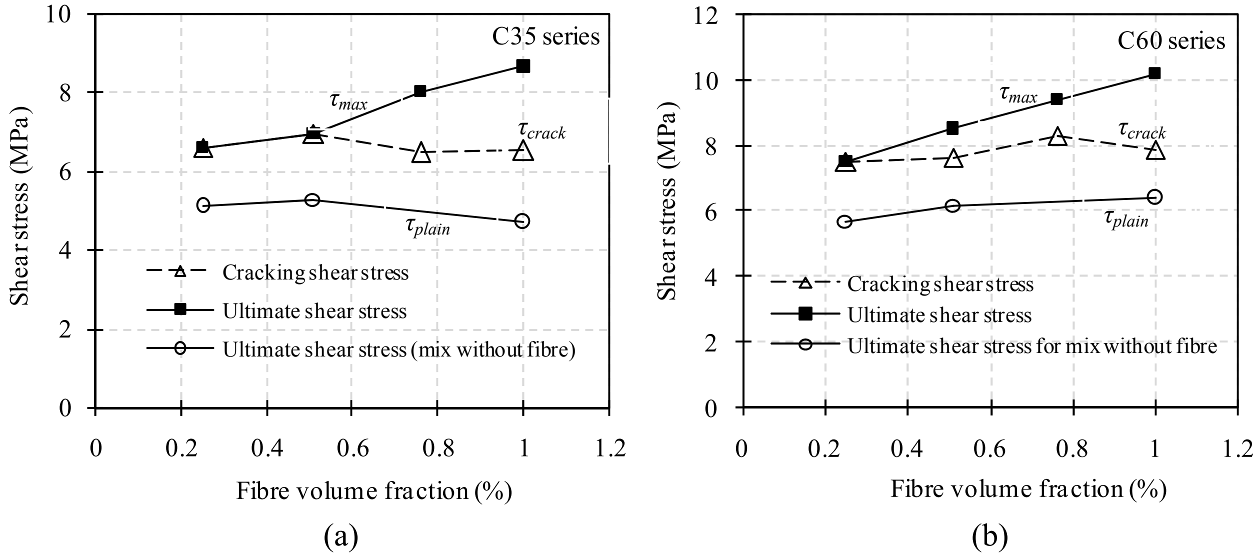


Figure 6. Shear stress test results versus fibre volume fraction: (a) C35 specimens; and (b) C60 specimens.

An empirical shear transfer model, based on the regression analysis, has been developed to predict the ultimate shear stress of SFRC. The proposed strength prediction model is a function of compressive strength of SFRC and its fibre volume fraction, and is expressed as

$$\tau_{\max} = 0.75\sqrt{f_c^{'}} + 4V_f^{0.9}$$

Where $f_c^{'}$ is compressive strength of the SFRC cylinder, and V_f is fibre volume fraction expressed as a percentage. Figure 7 shows a comparison of the test results and the predictions of the proposed model for ultimate shear strength of SFRC.

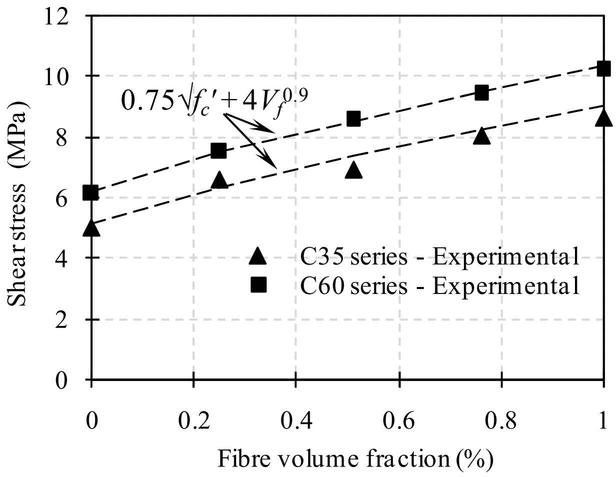


Figure 7. Comparison of test data of the present study and the proposed model for ultimate shear stress of SFRC.

CONCLUSIONS

The FIP shear test method was successfully used to obtain the shear performance of the SFRC and plain concrete. The results demonstrate that the addition of fibres leads to a ductile failure and improvements in post-peak response. The improvements in shear performance of SFRC were more significant for fibre dosages above 40 kg/m^3 in both normal and high strength concrete. Empirical model was derived, based on regression analysis, to predict the shear strength of SFRC specimens.

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